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Analysis of Spatiotemporal Properties in American Sign Language

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ABSTRACT

Careful measurements of the temporal dynamics of speech have provided important insights into phonetic properties of spoken languages. By contrast, analytic quantification of the visual properties of signed languages still is largely uncharted. Exposure to sign language is a unique experience that could shape and modify low-level visual processing for those who use it regularly (i.e., what we refer to as the Enhanced Exposure Hypothesis). The purpose of the present study was to characterize the spatiotemporal properties of American Sign Language (ASL) so that future studies can test visual perception in signers both within and outside the range of properties found in ASL. Using an ultrasonic motion tracking system, we recorded the hand position in 3-dimensional space over time during sign language production. From these data, we calculated several metrics: hand *position* and *eccentricity* in space and hand motion *speed*. For individual signs, we also measured total *distance* traveled by the dominant hand and total *duration* of each sign. These metrics were found to fall within a selective range, suggesting that exposure to signs is a specific and unique visual experience, which might alter visual perceptual abilities in signers, even for non-language stimuli.

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1. INTRODUCTION

Several lines of experimental evidence suggest that visual experience plays a role in shaping visual abilities during development (Kiorpes & Movshon, 2003). Generally, it is thought that human perceptual systems are most efficient at processing the signals that occur most frequently in the environment (Simoncelli & Olshausen, 2001). One of the best examples of this is in the domain of orientation processing; animals raised in restrictive environments containing only horizontal or vertical contours have heightened sensitivity for orientations they experience and poor sensitivity for those they do not (Blakemore & Cooper, 1970, 1971; Hirsch & Spinelli, 1970; Stryker, Sherk, Leventhal, & Hirsch, 1978). The effects of restrictive visual experience are also seen in humans who had an astigmatism as children. If this condition remains uncorrected, these children later develop meridional amblyopia, a condition of decreased visual sensitivity for orientations blurred by their astigmatism (Gwiazda, Mohindra, Brill, & Held, 1985; Mitchell, Freeman, Millodot, & Haegerstrom, 1973; Mitchell & Wilkinson, 1974). There is also evidence that even typically-developing humans show anisotropies in sensitivity for orientations based on the frequencies of orientations in their environment. Specifically, cardinal orientations (vertical and horizontal) are more prevalent in natural scenes than are oblique orientations, as shown by Fourier analyses of natural scenes (Baddeley & Hancock, 1991; Coppola, Purves, McCoy, & Purves, 1998; Keil & Cristobal, 2000; Switkes, Mayer, & Sloan, 1978; Van der Schaaf & Van

Hateren, 1996). This is offered to explain the well-known phenomenon in which humans have better sensitivity for cardinal orientations than for oblique orientations, referred to as the “oblique effect” (Appelle, 1972; Campbell, Kulikowski, & Levinson, 1966; Mitchell, Freeman, & Westheimer, 1967). Indeed, the cardinal bias measured with Fourier analysis is stronger for scenes of man-made or “carpentered” environments that contain structures and buildings than for naturalistic scenes of landscapes and bodies of water (Hansen, Essock, Olshausen, & Lewicki, 2004; Keil & Cristobal, 2000; Torralba & Oliva, 2003). This difference has been suggested to explain why people who live in less carpentered environments, such as the Cree Indians who live in prairie regions, exhibit a smaller oblique effect than people who live in highly carpentered environments (Annis & Frost, 1973). Together, these results observed for orientation sensitivity suggest that the visual system is modified by, and tailors to, visual statistics within the environment.

In the current study, we consider the case of exposure to a visual (sign) language, with the notion that exposure to the unique visual properties of sign language might similarly shape low-level visual sensitivity in those who use it regularly. Sign language comprehension requires detailed perceptual processing of motion, form, orientation and shape cues inherent in the hands and arms on the body, as well as on the face, and enriched exposure to these cues could enhance signers’ perceptual abilities (reviewed in Emmorey, 2001). Often, slight changes in a sign’s hand movement, while all other features such as handshape and location are held constant, can change meaning (for example, the signs, SERIOUS and MISS in ASL are very similar with slightly different movement patterns). Supporting the effects of experience with ASL, there are several studies showing that signers (both deaf and hearing) exhibit altered and/or enhanced visual abilities for aspects of visual processing that might be important for sign language, such as visual motion perception and face discrimination (Bavelier, Brozinsky, Tomann, Mitchell, Neville, & Liu, 2001; Bavelier, Tomann, Hutton, Mitchell, Corina, Liu, & Neville, 2000; Bosworth & Dobkins, 1999, 2002a; Brozinsky & Bavelier, 2004; Emmorey, Klima, & Hickok, 1998; Emmorey & Kosslyn, 1996; McCullough & Emmorey 1997, and see Poizner, 1983; McCullough, Brentari & Emmorey, 2000).

Given that experience with sign language alters visual processing, it is reasonable to predict that differences in visual processing between signers and non-signers might be greatest for visual stimulus properties that reflect those encountered in the sign language signal. For example, visual processing might be altered only for the speeds of motion or the orientations that represent those most frequently occurring in sign language and not those outside this range. To investigate this hypothesis, however, the visual properties of sign language signal must be characterized. We initially addressed this in a previous study, where we quantified the spatial frequency and orientation content of the articulators (hands and arms) during sign production by conducting Fourier analysis on a set of photograph images of many signs (Bosworth, Bartlett, & Dobkins, 2006; Bosworth, Wright, Bartlett, Corina, & Dobkins, 2003). The results revealed differences between the sign images and two other image sets (faces and natural scenes), particularly for orientation. Specifically, sign images were found to contain more amplitude for vertical than for horizontal contours, while images of faces and natural landscape scenes showed an opposite pattern. This stimulus specificity of orientation content in signs predicts that, when tested in perceptual and/or imaging studies, signers (compared to non-signers) might show enhanced/altered visual sensitivity to vertical, but not horizontal, orientations. We refer to this prediction as the “Enhanced Exposure Hypothesis”.

In order to further explore the visual image statistics of the sign language signal, in the current study we measured spatiotemporal properties, namely those related to location and motion of the signing hand through space. To determine these ranges, we used ultrasonic position trackers placed on the dominant hand to measure hand position in three-dimensional (3D) space over time from deaf subjects who were fluent in ASL as they produced 42 different signs. From these position coordinates recorded from each sign, we calculated retinal *eccentricity,* which is the average distance of the hand from the viewer’s fixation, *speed* as the hand moves through 3D space, *distance* traveled by the hand for each sign, and *duration* of each sign. Across 42 signs, we report the means and distributions of these measures. This provides a corpus of image statistics that can be used in designing future visual processing studies to test the Enhanced Exposure Hypotheses in signers, with a particular emphasis on location and speed of visual stimuli, as these stimulus parameters can be easily manipulated in studies of visual processing. Like the prediction mentioned above for orientation, the Enhanced Exposure Hypothesis predicts that differences in visual processing between signers and non-signers will be greatest for speeds and locations that fall *within* the range encountered in sign language.

In addition to providing image statistics that can be used to test the Enhanced Exposure Hypothesis, the spatiotemporal properties of sign language are interesting in their own right, similar to studies describing the temporal characteristics of spoken languages (e.g., Bellugi & Fischer, 1972; Fischer, Newkirk, & Bellugi, 1979; Grosjean, 1980; Wilbur & Nolan, 1986). To this end, we explored a secondary and conceptual question about the spatiotemporal properties of signs, which is whether signers might modulate the timing of their hand/arm movements to maintain some degree of constancy in either the speed or the duration of signs (or a combination of both). Although not the main purpose of this paper, these data could speak to a highly debated topic of whether articulatory *isochrony* exists in languages, a term that refers to the concept that production (or perception) of language units occurs regular intervals in time (Pike, 1945; Tuller & Fowler, 1980), perhaps in order to accommodate perceptual ease for the viewer, and/or articulatory constraints (such as muscle contraction or respiratory rates).

2. METHOD

Stimuli. Position and movement of the hands in space were recorded for 42 pre-selected signs in ASL, each individually produced by deaf signers who were fluent in ASL and used ~~in~~ ASL daily. Two signers (RB and DH) learned ASL in late childhood and one (VM) was a second-generation signer. We chose 42 different signs with the goal of creating a diverse sample of lexical items that represent various common phonological features. For the sake of consistency, we used the same signs that were analyzed in our previous study of the spatial frequency and orientation content of signs (Bosworth et al., 2006). (See *Appendix* for the list of signs used.)

Procedure. Hand position was measured using an InterSense 3-D motion measurement system at the Virtual Reality Laboratory at the University of California, Irvine. Three fluent female signers (RB, DH, and VM, tested separately) wore flexible, fingerless gloves with a small ultrasonic position tracker placed firmly on the back of each hand. These devices emitted ultrasonic signals at a rate of 15 Hertz, which were recorded by a receiver placed on the ceiling above the signer. These signals provided the x (horizontal), y (vertical), and z (depth) position of the hands every 66.7 milliseconds, as the subject signed (see example in *Figure 1*). Signers were asked to stand under the sensor which was mounted on the ceiling and produce each signed stimulus item at natural pace.

An experimenter recited each stimulus item to the signer, and when the signer was ready, she reproduced the item at her own comfortable speed. Signers were instructed to reproduce each of the 42 selected signs embedded within a carrier phrase, "SIGN X EASY", where X represents the sign of interest (which we refer to as the "target" sign). The English translation of this sentence is "To sign "X" is easy." The purpose of employing a carrier phrase was to eliminate the initial and final minima in movement followed by the rapid, explosive transitional movement from resting position into signing space. In doing so, this allows us to isolate each target sign being produced in their natural signing rates. For each phrase, the signer began and ended with her hands resting at her sides. Signers were asked to sign each carrier phrase three times. The purpose of this repetition was to calculate reliability in the signer's reproductions of each target sign. To this end, we calculated Cronbach's alpha using the determined speed of the target sign (methods described further below). Specifically, for each signer, we entered the average speed data for the three repetitions for the 42 signs, asking if there was internal consistency within each sign. Because we found high internal consistency α values (RB: α = 0.92, DH: α = 0.88, VM: α = 0.79), we used only the first production of each sign for the rest of our analyses.

Excising Target Signs for Analysis. For the purpose of this paper, we analyzed data only from the right (dominant) hand of each subject, since one-handed signs only use the dominant hand, and in two-handed signs, the dominant hand moves while the non-dominant hand remains either stationary or mirrors the dominant hand's movement. Because we were interested in analyzing the target signs, the first step of analysis involved excising data corresponding to the target sign from the carrier phrase, which was done with script written in Matlab. First, the x,y,z position over time for each carrier phrase was plotted using MATLAB 3-D plotting tools (Matlab 2015b). The Matlab script served to demarcate where the target sign began and ended. This was based on movement patterns that were fairly consistent across the different samples (within each signer) for the non-target signs (SIGN and EASY) of the carrier phrase. The start of the carrier phrase was characterized by a large initial change in the vertical position of the hands, resulting from both hands rising from the resting position (i.e., signer's hands at sides), followed by cyclic repetition in the vertical dimension, resulting from generating the word "SIGN". Likewise, the end carrier phase was characterized by two rapid changes in vertical position, resulting from generating the word "EASY", followed by a large change in vertical position, resulting from the hands returning to their resting state (see *Figure 1*). Authors ST and RB evaluated each excised sign and were in agreement as to the start/end points of the target sign. In the rare case of disagreement, the two authors analyzed the carrier phrase together, and came to an agreed upon solution.

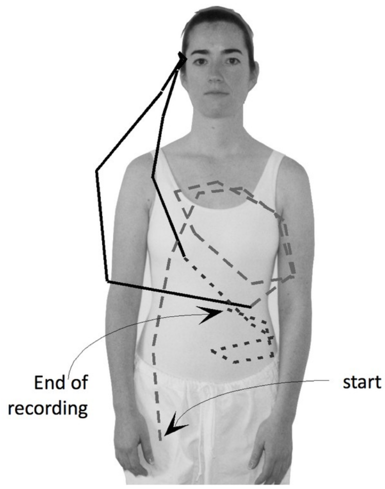

Figure 1. Example 2-D motion trajectory. Position (x, y) of the right dominant hand for the ASL phrase, SIGN KNOW EASY (English gloss: "To sign the word 'know' is easy") is plotted. In this example, the target sign is KNOW, represented by the solid line, while the carrier phrase is represented by the dashed line, with larger dashes used for SIGN and smaller dashes for EASY. (The z dimension not shown here was also recorded.)

Measures. For each signer, and for each target sign, we recorded position coordinates of the hands over time, where *x* is a "lateral" plane in front of the signer that moves to the left or the right of the signer, *y* is height of the hand, as the hand moves up and down, and *z* is the plane that moves in front of versus behind the signer's body. We defined the origin (0, 0, 0) as the point in between the signer's eyes, which was chosen with the assumption that this is an estimate of where a viewer looks when watching another person sign. Positive values were y values that are above the eyes, x values that were to the right of the body midline, and z values that were in front of the body. From these position coordinates, we calculated the following metrics for each sign:

1) *Position* in space of the dominant hand, at every time sample. From these data, we calculated an *eccentricity* value for each time sample, defined as the ~~centimeters~~ distance (centimeters) from the origin.
2) *Total distance*, reported in centimeters, was calculated by summing the distance traveled (~~for each x, y, and z~~in three dimensions) between all consecutive samples in 3D space.
3) *Total duration,* reported in seconds, was calculated by subtracting the end timestamp from the first timestamp of the target sign.
4) *Speed,* Instantaneous speeds were calculated as the change in position coordinates distance from one to the next sample in time (i.e., distance/time). This change in distance was solved using the Pythagorean theorem, solving for the hypotenuse (i.e., distance between two points in space) of a right triangle, s $=\sqrt{x^2+y^2}$. For 3D speeds, this was s $=\sqrt{x^2+y^2+z^2}$.

For *eccentricity* and *speed,* we present the data in centimeters and also in degrees of visual angle. This is because the visual system encodes the world in visual degrees and, therefore, this is the relevant dimension (not absolute size in cm) when referring to a signer's visual experience. Equally important, if future studies test the “enhanced exposure hypothesis”, we need to know the properties of signs in degrees, so we can recreate those conditions on a video monitor. Note that when presenting the results in degrees, we use only the x, y (2D, frontoparallel) plane, since this is the plane projected on (and “experienced” by) the 2D retina. (In addition, future studies that test the Enhanced Exposure Hypothesis will likely use 2D monitors, which can only replicate the x, y spatiotemporal properties of signs). As in our previous study, to determine degrees we assumed a viewing distance of 5 feet in front of the signer, with the estimate that signers stand roughly 5 feet apart when conversing (see *Discussion* for more details Bosworth et al, 2006). Degrees of visual angle (in degrees) was calculated as $\tan^{-1}(x/152) * (180/pi)$, assuming a viewing distance of five feet (i.e., 152 centimeters).

Means and Distributions. For each of our measures, we calculated means and distributions for each of the three signers. For duration and distance, means were calculated across all samples for each of the 42 signs. For eccentricity and speed data, calculated means were derived from *all* samples, across all signs. We chose to do it this way to give more weight to signs of longer duration (for example, if the duration of two signs were 167 msec and 333 msec, the number of samples that went into the average was 10 and 20, respectively), since our goal was to get an estimate of distribution of the eccentricity and speed of hands when signing in the real world, which will be affected more by longer signs[1]. The total number of eccentricity samples was 529, 452, and 406, respectively for RB, DH, and VM. The total number of speed samples was 487, 410, and 337, respectively for RB, DH, and VM.

Modeling Constraints on Signing. Intuitively, signs will vary in how fast and how far the hands travel through space. With our distribution of speeds, we asked whether signers modulate their hand/arm movements in a systematic way that maintains some degree of invariance in either the speed or the duration of signs. Such would be predicted by a premise of *articulatory isochrony*, where the durations of signs are relatively invariant despite a large variation in distance. For example, if signers are trying to maintain a constant speed, hand speed would be about the same regardless of whether the hand traveled a short or long distance; conversely, if signers are trying to maintain a constant duration, hand speed would be faster for signs that take up more distance (and vice versa). To address this question, we plotted speed vs. distance for each signer (across the 42 signs), asking whether the resulting function was more in line with a constant speed (i.e., a slope of 0, with the mean equal to the mean speed of signs, for a given signer) or a constant duration (i.e., a non-zero slope, with the slope equal to

[1] We admit that this argument assumes we picked 42 signs whose durations reflect an accurate representation of the durations present in all signs. Given that we were careful to sample many different types of signs, we believe our selection is likely sufficient.

the mean duration of signs, for a given signer). (For obvious reasons, we used 3D physical motion in centimeters (and not degrees) in this analysis.)

3. RESULTS

Eccentricity

Figure 2 presents a scatterplot of all sample position coordinate values from all time samples of all signs. From these values, we computed average visual eccentricities from the origin (i.e., midway between the signer's eyes), which are presented in *Table 1* as means and SDs. Here, we present the results in degrees in 2D (X, Y) space, assuming a 5-foot viewing distance (however, Table 1 also presents centimeters in 3D space, i.e., X, Y and Z

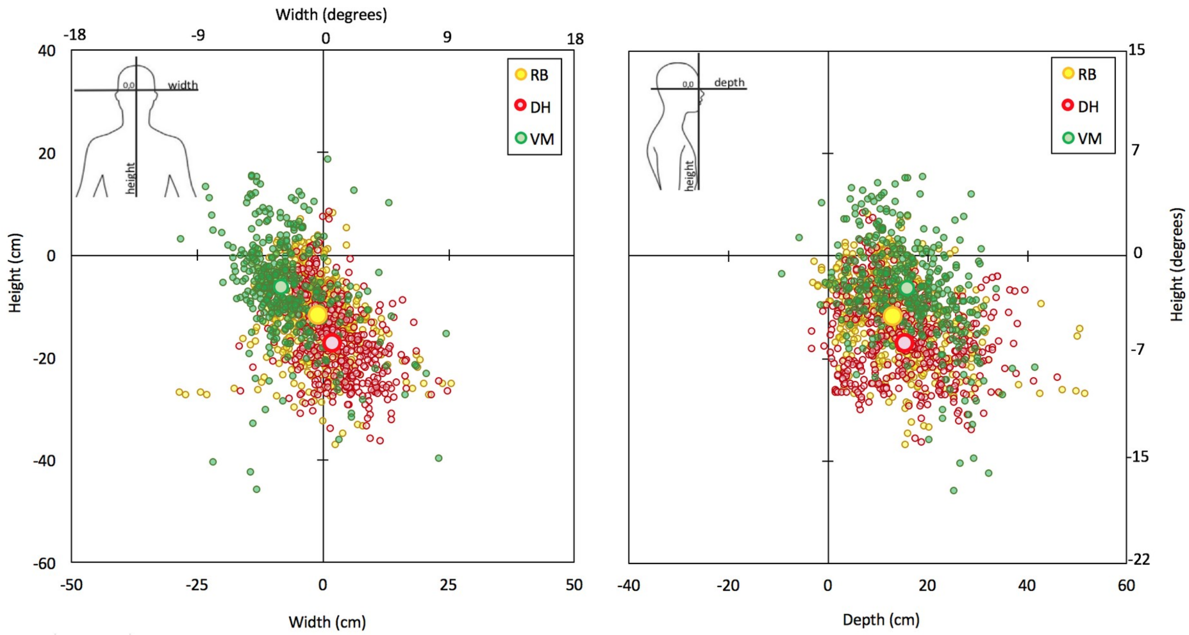

Figure 2. Scatterplot of hand position over time. Position coordinates are shown for all samples, from all 42 signs, separately for the three signers. On the *left*, values are plotted for height (y) and width (x), assuming one is facing the signer. On the *right*, values are plotted for height (y) and depth (z), assuming one is viewing a signer from her right side profile. Position values are presented in terms of centimeters and, for x and y, degrees from the origin (between the eyes, in front of the face, defined as 0,0,0). For each signer, a larger circle depicts the average position.

dimension). Across the three signers and all signs, Y position of the right hand appears, on average, 4.4 degrees below the signer's eyes, with the 95% CI range as 2.8 degrees above to 11.8 degrees below signer's eyes.[2] The X position of the hand appears, on average, 0.6 degrees to the viewer's left (i.e., very close to midline) with a 95% CI range from 6.2 degrees to the viewer's left and 5.0 degrees to the viewer's right of midline. The eccentricity from origin is about 5.7 degrees of visual angle, with a 95% CI range of 0.1 to 11.3 degrees. Should the signer be closer in distance, this eccentricity range will be larger. For example, for a signer who is 3 feet away, the signs fall roughly 9.4 degrees of visual angle from fixation (with a range of 0.3 to 18.5 degrees).

Table 1. *Averages and Standard Deviations for position coordinates and eccentricity, calculated from all samples.*

	3D space (centimeters)				2D space (degrees)		
	X	Y	Z	Eccentricity from origin	X	Y	Eccentricity from origin
Signer 1 (RB)	-0.9 (6.3)	-11.9 (7.7)	13.8 (8.3)	20.4 (9.1)	-0.3 (2.4)	-4.5 (2.9)	5.1 (2.7)
Signer 2 (DH)	2.6 (6.2)	-16.3 (8.1)	15.6 (9.3)	24.9 (9.3)	1.0 (2.3)	-6.1 (3.1)	6.6 (2.9)
Signer 3 (VM)	-7.2 (7.1)	-6.0 (11.1)	15.6 (10.1)	22.6 (9.8)	-2.7 (2.7)	-2.2 (4.2)	5.3 (2.8)
Average	*-1.5 (7.6)*	*-11.7 (9.8)*	*14.9 (9.2)*	*22.6 (9.6)*	*-0.6 (2.9)*	*-4.4 (3.7)*	*5.7 (2.9)*

Distance, Duration, and Speed

Statistics for distance and duration are presented in *Table 2.* The average distance and duration across all signs and signers were 57 cm (95%

[2] As stated in the *Methods*, we use only x and y coordinates when referring to visual eccentricity, assuming a viewer is standing in front of a signer from a distance of five feet. Likewise for motion statistics, we refer to 3D speeds when referring to physical hand motion through space, and 2D (x,y) speed when referring to the speed of visual motion, as the z plane is minimally accessible to the human visual system.

CI range: 8 to 121 cm) and 779 seconds (95% CI range: 30 to 1,529 seconds), respectively.

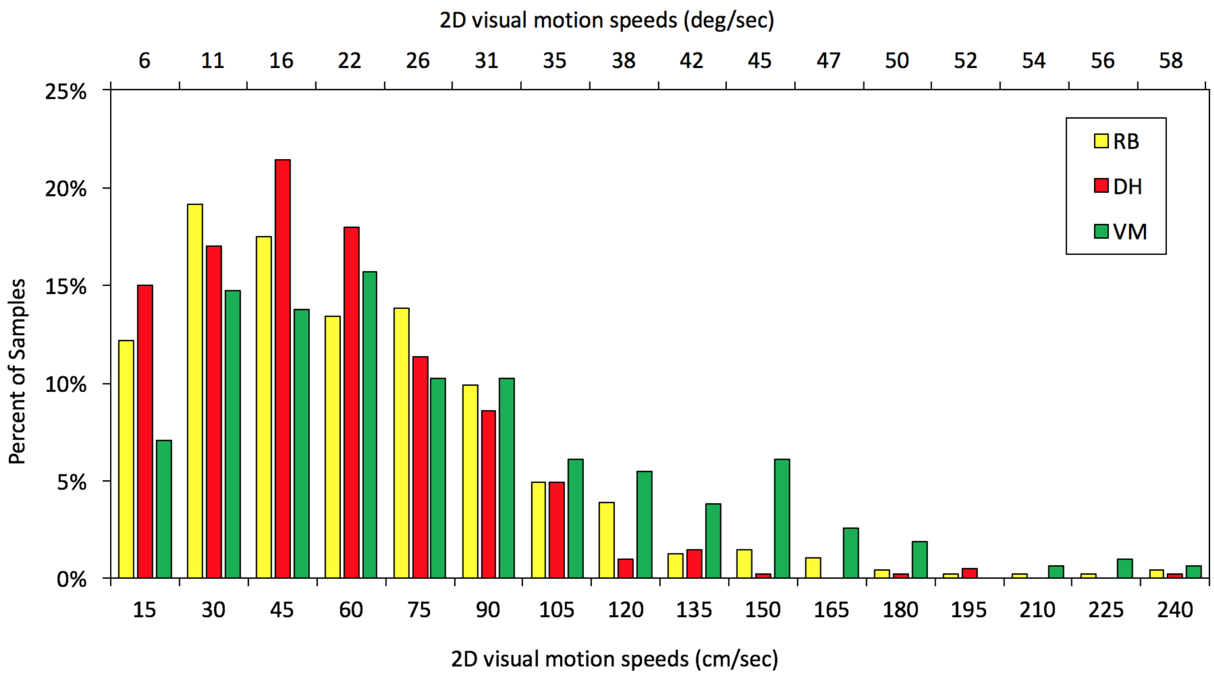

Figure 3. Frequency histogram of 2D speeds for each signer. The average speed was 19 deg/sec The median speed was very similar, at 17 deg/sec.

Results for speed for each signer are also presented in *Table 2*. The average 2D visual motion speed (across 3 signers) was 19.2 deg/sec (95% CI range: 3.8 to 34.5 deg/sec). *Figure 3* presents the frequency distribution of 2D speeds separately for each of the three signers. The distributions for the signers show a normal shape with occasional very fast speeds creating positive skews. The mean 2D speed for VM was 23.9 deg/sec, while for RB and DH, it was 17.9 and 16.0 deg/sec, respectively.

The average 3D physical motion speed across all three signers was 79.2 cm/sec (95% CI: 17.6 to 140.9 cm/sec). VM's average speed was 103.4 cm/sec, while RB and DH were very similar, at 69.7 and 64.6 cm/sec.

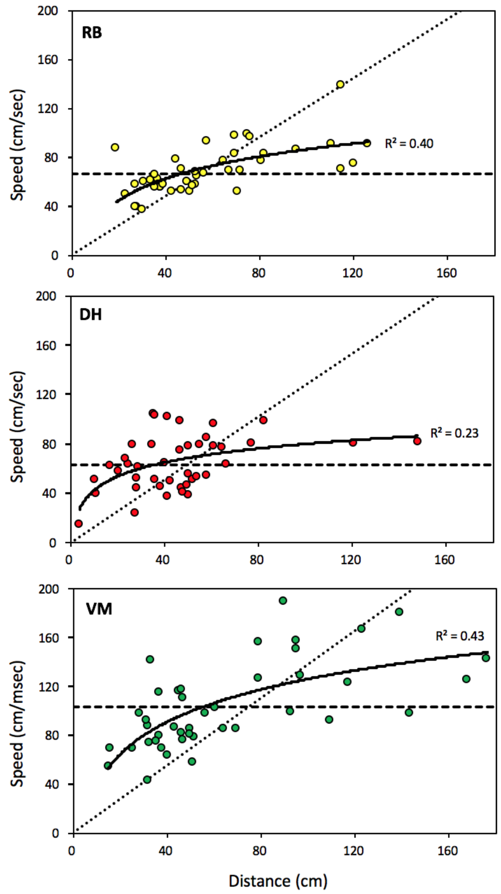

Figure 4. Speed vs. Distance Plots. 3D Speed (in centimeters per second) and distance (centimeters) values across all signs are plotted in separate figures for the three signers, RB, DH, and VM. For each signer, each dot represents the average speed value of a single sign as a function of the sign's cumulative distance traveled by the hand. The dashed line is the model of constant speed, the thin line is the model of constant duration (see text). The bold line is a logarithmic fit, and the

Relationship Between Sign Duration and Distance. To address whether signers might try to constrain either the speed or the duration (or both) across variations in total signing distance, we plotted speed vs. distance for each signer (across the 42 signs), asking whether the resulting function was more in line with a constant speed (i.e., a slope of 0, with the mean equal to the mean speed of signs, determined separately for each signer) or a constant duration (i.e., a non-zero slope), or some combination of the two.

The plots are shown in *Figure 4*, separately for each of the three signers. For each signer (and each figure), a constant *speed* is modeled by the dotted diagonal line, calculated for each signer based on the average duration and distance traveled across all signed samples, whereas a constant *duration* is modeled by the horizontal dashed line, also calculated based on the average duration for each signer. For all three signers, a logarithmic fit provided a very good fit, as follows: RB: $r = 0.63$; DH: $r = 0.48$, VM: $r = 0.66$, with all fits highly significant ($p < 0.001$). It may be that signers try to constrain duration for signs of shorter distances (i.e., the slope relating speed vs. distance was close to the mean duration of signs), yet constraining speed for signs of longer distances (i.e., the function relating speed vs. distance started to flatten out at longer distances). We address this, and other possibilities, further in the *Discussion.*

4. DISCUSSION

The results of this study provide statistics about the spatiotemporal properties of signs in sign language. We were interested in quantifying these properties so that future studies could test whether frequent exposure to sign language alters visual processing, i.e., the “Enhanced Exposure Hypothesis”. The data from this study also allowed us to ask whether signers might modulate the timing of their hand/arm movements to maintain some degree of constancy in either the speed or the duration of signs (or a combination of both). We address each of these, in turn, below, as well as addressing whether or not spatiotemporal properties of signs may be a truly unique experience for signers.

Testing the Enhanced Exposure Hypothesis. The "enhanced exposure hypothesis" predicts that differences in visual processing between signers and non-signers are predicted to be greatest for the visual properties that fall within, versus outside, those encountered in sign language. Although studies directly testing this hypothesis for sign language have yet to be performed, there does exist some data from previous studies that allow us to take a first step in addressing this. Specifically, we can ask whether previous studies that observed differences in visual processing between signers and non-signers used stimuli whose properties fell within the range of those observed for sign language in the current study. For this question, the most obvious visual measures to explore are speed and visual eccentricity in studies of motion processing, as these are well-controlled in visual studies.

In this domain of motion processing, perhaps one of the most robust differences between signers (both deaf and hearing) and non-signers is in hemifield asymmetries; whereas non-signers show either no visual field asymmetry or a slight left visual field (LVF) advantage, signers show a strong and significant right visual field (RVF) advantage for motion tasks (Bosworth & Dobkins, 1999; Neville & Lawson, 1987a). This effect for motion processing has been shown using lateralized stimuli for a leftward vs. rightward direction-of-motion discrimination task (Bosworth & Dobkins, 1999, 2002b; Samar & Parasnis, 2005), an apparent motion task (Neville & Lawson, 1987a, 1987b), and a speed discrimination task (Brozinsky & Bavelier, 2004). Supporting these behavioral results, deaf and hearing signers show greater brain activation in the left hemisphere while viewing moving stimuli compared to hearing non-signers (Bavelier et al., 2001; Neville & Lawson, 1987b). Since the left hemisphere is believed to be dominant for sign language processing Poizner, Battison, & Lane, 1979; Corina, Vaid, & Bellugi, 1992), the RVF (i.e., left hemisphere) advantage in signers has been attributed to a “language capture” effect, wherein motion processing gets usurped by the left, language-dominant hemisphere because motion is an integral part of *comprehending* sign language.

Given the altered visual field asymmetries seen in deaf and hearing signers for motion tasks, we are in a place to ask whether the speeds and eccentricities of the stimuli used in those studies were within the range of those observed for sign language in the current study. To this end, we looked at the speeds and eccentricities reported in empirical studies that reported altered visual processing in signers, in the form of a right visual field advantage. In terms of *speed*, values in these previous empirical studies ranged from 3 to 10 degrees/sec. In terms of *eccentricity*, values ranged from 4 to 18 degrees in the x dimension (i.e., stimuli tested at both left and right of fixation), and from 0 (i.e., aligned with fixation) to 13 degrees (i.e., above/below fixation) in the y dimension. In the current study, we found that the mean speed of signs (in the x, y plane) across the three signers was 19.2

deg/sec, with a 95% CI of 3.8 to 34.5 deg/sec. For eccentricity of signs, the same analysis reveals the following. In the x dimension, the 95% CI ranges from about 5.0 to 6.2 degrees to the left and right of the signer's eyes. In the y dimension, the 95% CI ranges from about 2.8 degrees above and 11.6 degrees below the signer's eyes. From this exercise, we conclude that the speeds used in previous studies of visual processing in signers were in the (low) range of speeds encountered in sign language. Similarly, for eccentricity, those used in previous studies of visual processing in signers were in the range of those encountered in in the current study. Of course, this comparison between parameters used in previous empirical studies and those observed in sign language depends on what assumptions the current study makes when converting cm to degrees. In the current study, we converted cm to degrees, assuming that signers converse at about 5 feet from one another (see *Methods, also see below)*. If, for example, the conversing distance were closer to 10 feet, then our calculations of speeds and eccentricities get halved (i.e., 95% CI ranges from about 3.8 to 34.5 deg/sec), and then the speeds used in previous studies of visual processing in signers (i.e., 3 to 10 deg/sec) overlap quite well with those encountered in sign language.

Given that there is in fact, overlap with previous studies, then at least one aspect of the "enhanced exposure hypothesis" appears to be true, that signers exhibit altered visual processing for spatiotemporal parameters that fall within those encountered in sign language. What has yet to be tested (within the same study) is the converse hypothesis, i.e., signers will *not* exhibit altered visual processing for spatiotemporal parameters that fall *outside* those encountered in sign language (for example, speeds of 90 degrees/sec, or eccentricities of 25 degrees). Future studies will be needed to test this hypothesis further. The strongest test of the hypothesis will involve ~~tested~~ testing *two* sets of spatiotemporal parameters; one within, and one outside, the range encountered in sign language. In addition, it will be important to test both deaf and hearing signers, to determine whether differences are due to sign language experience vs. deafness.

Constraints on Signs. In our analysis that looked at whether signers might try to constrain their arm/hand movements as they sign, we found evidence for systematic variation in both the speed and duration of signs in our correlation analyses of speed vs. distance. Because the data were well fit with a logrithmic function, this suggest that signers may try to constrain duration for signs of shorter distances, yet constrain speed for signs of longer distances. The results of our analysis suggest that the variance we observed in the speed and duration of signs is systematic, rather than random, in nature.

If there is systematicity in rate of signing, the interesting question arises as to why this might be the case. On the one hand, it might be the case that the speed of arm/hand movements in sign language is limited by biological constraints (i.e., how fast the muscles can move), and as such, is not under the volition or cognitive control of the signer. On the other hand, it might be that signers use speeds that stay within the bounds of those that are comprehensible to a viewer, and that this is under the volition of the signer. Research on the speed of arm movement find an upper limit of around 150 – 250 cm/sec when participants must quickly raise an arm to stop an oncoming obstacle (DeGoede, Ashton-Miller, Liao, & Alexander, 2001). Because this is well above the hand speeds observed in the current study, we do not think the speed of signs is under a biological constraint.

With respect to *comprehension* constraints, it is intuitive that signers will choose to sign at a speed that is within the bounds of those that are comprehensible for the viewer. As is likely the case for spoken language too, presumably the goal for signers is to sign as fast as they can, but not so fast that the listener/viewer cannot follow (and anyone conversing with someone new to a language naturally knows to slow down the pace). In a relevant study by Fischer, Delhorne and Reed (1999), the relationship between speed and comprehensibility was investigated by presenting signers with videos of people signing at different playback speeds. To this end, they first videotaped native signers signing 98 different words. [NOTE: They reported a mean duration of 1100 msec, which was about 1.4 longer than observed in the current study (780 msec averaged across the three signers). This difference is likely due to their study presenting isolated signs, including transitional movement from resting position, while our study used signs produced at a natural pace within sentences.] The researchers then tested comprehension in subjects who were fluent in sign language, who were asked to watch the videotapes of the signs and report each word they saw, at different playback speeds. The results of this study showed that comprehension fell from 98 to 46% as signs went from the normal speed/duration to 6x, with impairments seen at about 3x[3] normal rate. This result is consistent with the possibility that signers use speeds that are within the bounds of those that are comprehensible in sign language.

Are the Speeds Inherent in Sign Language Unique? As a final point, we address how the speeds of signs compare to speeds of other common objects in the environment (people walking, flying birds, cars, etc.) to get a sense of whether signing speeds are a unique experience. For this, we start with estimating cm/sec, and then, address the conversion of speed into degrees/sec. Perhaps the two most common objects we see move in our environment are walking people and moving cars. For people walking, it is estimated that a common walking speed is 3 miles/hour, which converts to 134 cm/sec. This speed is about 1.7 faster, although certainly within the range, of that occurring in sign language (across 3 signers, we found a mean speed of 79 cm/sec). This overlap in speed between humans signing and walking is not surprising, given that there is some biological constraints placed by the muscles of the human body (see above). For cars, we

[3] This translates to impairments at about 366 msec, which was half the mean duration of signs we observed in the current study.

estimate that they move between 30 – 60 miles/hour, which translates to 4 – 8K cm/sec, and of course, is much faster than the speed of signs.

Next, we turn to a comparison of signs, people walking and moving cars, all in terms of degrees/sec. As repeated throughout this paper, determining *degrees/sec* depends on the viewing distance, and therefore assumptions must be made about this metric. For *sign language*, viewing distance ought to be largely constrained (and we assume a distance of about 5 feet), for two reasons. First, social etiquette dictates a comfortable distance between conversers (which is true for both signed and spoken language). Second, too far of a distance between conversers will hinder comprehension, either because of occlusion from other objects (e.g., if someone walks in between the two conversers) or an inability to resolve the articulators (fingers, hands, arms) at a far distance. By contrast, viewing distance for walking people or moving cars is far less constrained (i.e., people/cars can be very nearby or very far away). As such, degrees/sec of walking people and moving cars can vary quite a lot, with a faraway person (perhaps 200 ft) moving as slowly as 1.3 degrees/sec and a nearby car (perhaps 10 feet away on a city street) moving as fast as 85 degrees/sec. This large speed range (about 1 – 85 degrees/sec) for other common moving objects in the environment encompasses those encountered in sign language determined from the current study (across 3 signers, we found a mean 2D (x,y) speed of 19 degrees/sec).

Given the large range, it seems unlikely that the speed of hand movement in sign language provide a *unique* experience for signers. We have previously addressed the significance of non-uniqueness in our study that characterized the spatial frequency and orientation makeup of signs (using Fourier analysis, Bosworth et al, 2006), because in that study, we observed a unique orientation bias, but not a unique spatial frequency bias, for signs. Specifically, compared to faces and natural scenes, which contained more amplitude for horizontal than vertical contours, signs showed the opposite pattern. However, like the current analysis of speed, the Bosworth et al. study did not find evidence for a unique spatial frequency bias in signs (i.e., signs, faces, natural scenes all showed the classic 1/f curve). We argued in that paper, as we will argue here, that uniqueness, while interesting if it exists, is not a necessary prerequisite for the "enhanced exposure hypothesis", which is why we did not refer to it as the "*selective* exposure hypothesis". In other words, we argue that -- whether or not the visual properties of sign language are unique, signers will get *more* exposure to these properties than do non-signers (and of course, rely heavily on these signals for comprehension). According, we propose that whether or not the spatiotemporal properties of sign language are unique, the "enhanced exposure hypothesis" is an important hypothesis to test.

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APPENDIX

Sign Stimuli:

One-handed signs: CANADA, FOOD, GOAT, HEART-FELT, KNOW, MINE, ASK, FIND, SHUT-UP, THROW, CAT, MAIL, SPIT, SUMMER, FACE, GIVE, REJECT, SMART, TELL, VOMIT, GIVE-continuously, TELL- continuously

Two-handed signs: ABORTION, DOCTOR, BICYCLE, ENJOY, GESTURE, LONG-AGO, WASH, HAVE, SICK, HATE, DAMAGE, STEAL, ARREST, SEND, IMPROVE, READ, UNTIL, YEAR, READ-continuously, SICK-continuously